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ROOFTOP RUNOFF FOR WATER SUPPLY

By W. O. Ree[1]

ABSTRACT

Measurements of rainfall, rooftop runoff, wind direction, and wind velocity were made for 1 year to determine the practicality of harvesting rainfall on rooftops and to develop a method for predicting the probable yield of a sloping roof from available rainfall and wind data. The gable roof of a laboratory building was used for this experiment. A 6-inch plastic downspout conveyed water from the gutters to flow-measuring flumes on each side of the building. FW–1 recorders with 6-hour gears were used to obtain a time-head record, and rainfall was measured with a recording rain gage. Miles of wind were measured with a three-cup anemometer. The roof side facing windward delivered about 96 percent of the rainfall as runoff, and the leeward side delivered about 89 percent. However, only 50 percent of snowfall was captured as runoff. A recovery of 90 percent of all precipitation as runoff would be a satisfactory assumption for design purposes in the test area. Present hydrologic design methods can be used for designing rain-harvesting systems if an estimate is made of the ratio of runoff to rainfall. **KEY WORDS: rooftop runoff, storm-wind directions, water supply, wind amounts.**

INTRODUCTION

Water for remote, arid areas may be obtained by harvesting rainfall on rooftops. The practicality of this source is considered in this paper, and criteria for estimating the water yield of rooftops are presented.

C. W. Lauritzen[2] showed that rainfall harvesting for water supply was practical by using impervious sheets on the ground to trap raindrops and by using covered leakproof tanks to store the collected runoff. Ree et al.[3] subse-

quently developed a hydrologic design procedure to determine the size of the impervious sheet and the tank volume needed to permit a given water-use rate from storage with the percentage probability of having water a parameter. The basis for the design method was a probability analysis of past minimum rainfall periods. An important assumption in this procedure was that runoff is 100 percent of rainfall.

These earlier studies showed that wherever rain fell on an impervious surface a dependable water supply could be assured by the proper design, installation, and maintenance of a rain-trap system, provided the rainfall probability estimates upon which the design is based are dependable. In this sense the method was practical but relatively expensive. When the costs of these installations were examined, some observers felt that they would rather have invested the money in a shed roof and thus have had a shelter as well as a raintrap. This was an attractive idea, but there was considerable un-

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[2] Lauritzen, C. W. 1967. Butyl—for the collection, storage, and conveyance of water. Utah Agric. Exp. Stn. Bull. 465, 41 pp.

[3] Ree, W. O., Wimberley, F. L., Gwinn, W. R., and Lauritzen, C. W. 1971. Rainfall harvesting system design. U.S. Dep. Agric., Agric. Res. Serv. [Rep.] ARS 41–184, 12 pp.

certainty over the effect of wind on the rainfall harvest. A sheet on the ground, where wind velocities are lowest, would perform differently from an elevated shed roof where wind velocities are higher and excess turbulence attributable to the shed itself occurs. So an experiment was undertaken to determine the runoff characteristics of a sloping roof, with particular attention given to wind effects.

The objective of the experiment was to develop a method for predicting the probable yield of a sloping roof from available rainfall and wind data. Three questions were encountered in pursuit of this objective. (1) Do wind direction and velocity affect the rainfall catch and delivery of a sloping roof? (2) From which direction does wind come during a rain? (3) Does this wind direction differ from the average wind direction reported in the available wind data for the location? The answers to these questions required measurements of rooftop runoff and corresponding rainfall amounts and also measurements of wind direction and velocity. The apparatus used for making these measurements and the measurement results are described in this report.

THEORY

A theoretical approach was developed in an attempt to answer the first of the three questions. In figure 1 vector P' represents the rainfall; its length is proportional to the rainfall amount passing through a unit area normal to the flow path. The angles ϕ and α are its direction with respect to the horizon and a reference meridian, respectively. A rain gage, with its opening in a horizontal plane, will receive $P' \sin \phi$ units of rainfall. The angle α will not affect the catch.

Place a sloping roof in this same rain-flow field and determine the unit rainfall catch of the roof. Let a horizontal element of the roof be the reference meridian. The direction of the horizontal component of the rainfall vector with respect to the meridian is α. The angle of the rainfall vector with respect to a horizontal plane is ϕ. The slope of the roof is S.

It is evident from figure 1 that the vertical component of the rainfall is $P' \sin \phi$. The roof will receive an additional or lesser amount, P_h, depending upon the magnitude of the angles ϕ, α, and S. This amount is given by the relation

FIGURE 1.—Diagram of rainfall vectors in relation to a sloping rooftop.

$$P_h = P' \cos \phi \cos \alpha \tan S.$$

For roofs sloping toward the wind, $\tan S$ is positive, and for those sloping away, $\tan S$ is negative.

The total unit rainfall, Q_w, on the roof is

$$Q_w = P' \sin \phi + P' \cos \phi \cos \alpha \tan S.$$

The ratio of rooftop runoff to the rain-gage catch is

$$\frac{Q_w}{P} = \frac{P' \sin \phi + P' \cos \phi \cos \alpha \tan S}{P' \sin \phi}$$

or

$$\frac{Q_w}{P} = 1 + \frac{\cos \phi \cos \alpha \tan S}{\sin \phi}$$

or

$$\frac{Q_w}{P} = 1 + \cot \phi \cos \alpha \tan S. \tag{1}$$

The second term of the right-hand part of the equation is the horizontal component of the rain expressed as a ratio of the vertical component. This component can be negative or positive.

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The use of equation 1 to estimate the rainfall caught by a sloping roof requires values for the angle ϕ, and such values are not available in weather records. However, an estimate of ϕ can be made if it is assumed to be a function of horizontal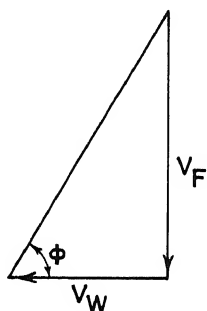 wind velocity. Measurements of wind velocity are readily made and are on record. Wind velocities and directions were measured in this experiment.

It is assumed that the tangent of the angle ϕ is the ratio of the vertical component of the raindrop velocity to the wind velocity. The geometry of this assumption is portrayed in the following sketch:

where V_F=fall velocity of the raindrop
and V_w=wind velocity.

A value of raindrop fall velocity for this analysis was obtained from a report by J. Otis Laws[4] containing measurements made during rainstorms. He found that fall velocity increased with drop size. Since the size of the raindrops in the rooftop experiment is not known, the corresponding fall velocity cannot be read from a graph provided by Laws. Instead, an average value of the velocities he reported is used, 7.5 meters per second or about 16.8 miles per hour.

Equation 1 can be written in terms of wind velocity if the following substitution is made for ϕ:

$$\phi = (\tan^{-1}\frac{16.8}{V_w}),$$

where V_w=wind velocity (miles per hour).

Since $\cot(\tan^{-1}\frac{16.8}{V_w}) = \frac{V_w}{16.8}$, equation 1

becomes $\frac{Q_w}{P} = 1 + \frac{V_w}{16.8}\cos\alpha\tan S.$ (2)

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[4] Laws, J. Otis. 1941. Measurement of the fall-velocities of waterdrops and raindrops. U.S. Dep. Agric., Soil Conserv. Serv. [Rep.] SCS–TP–45, 33 pp.

INSTALLATION AND MEASUREMENTS

The rooftop selected for this experiment is on the model building at the Water Conservation Structures Laboratory. This building is situated among a group of buildings that probably have some effect on wind patterns. However, the model building is the tallest of the group, so it is assumed that the other buildings have little effect on wind circulation around it. Figure 2 shows the arrangement of the buildings and their heights. The model building is a prefabricated steel structure 40 feet wide, 60 feet long, and 16 feet high at the plate line. The roof is a simple gable with a slope of one on three and a ridge height of about 23 feet. The orientation of the building is nearly east to west.

Spatially varied flow theory was used to calculate the size and slope of the roof gutter needed to convey the runoff from a 100-year, 5-minute intensity rainfall. Two 6-inch plastic downspouts conveyed the water from the gutters to flow-measuring flumes on each side of the building (fig. 3). The 9-inch H-flumes were
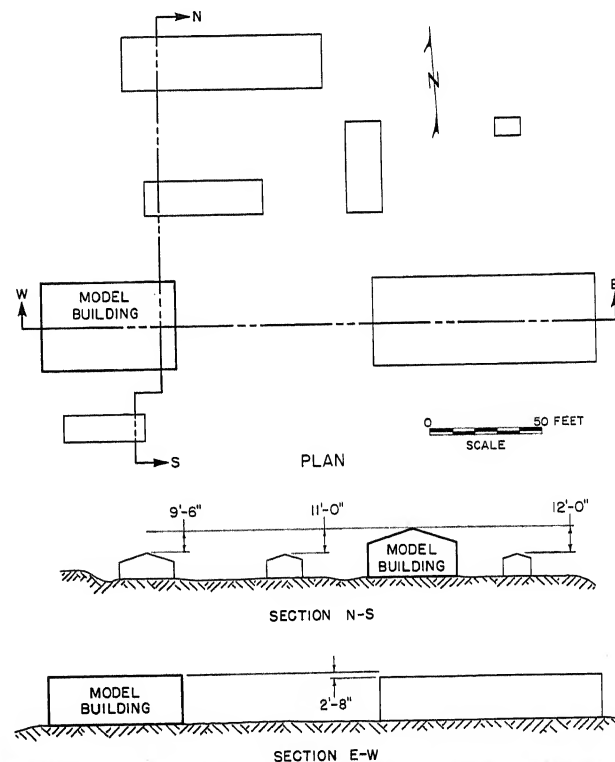

FIGURE 2.—Locations and heights of model and surrounding buildings.

from an earlier experiment (for which they were calibrated during installation on the approach box) and were considered quite accurate (±2 percent). However, they were not sensitive enough to provide an accurate measurement of the low-rate snowmelt flows of long duration. Heating coils were provided in the gage wells and beneath the flume floors to permit winter operation but were not installed on the roof or gutters. FW–1 recorders with 6-hour gears were used to obtain the time-head record.

Rainfall was measured with a recording gage located about 300 feet south of the model building. The catch of this gage was checked by comparison with the catch of a nearby standard gage. The 24-hour chart on the rain gage had time graduations only every 15 minutes, thus the 5-minute intensities reported are not very accurate because of errors introduced by visual interpolation.

Miles of wind was measured with a three-cup anemometer located near the rain gages and about 21 feet above ground. Since this was about midheight of the rooftop, the winds measured were probably representative of those at the building roof. The wind miles were recorded along with wind direction on the same chart. This chart was changed every 24 hours, at which time the digital totalizer on the ane-
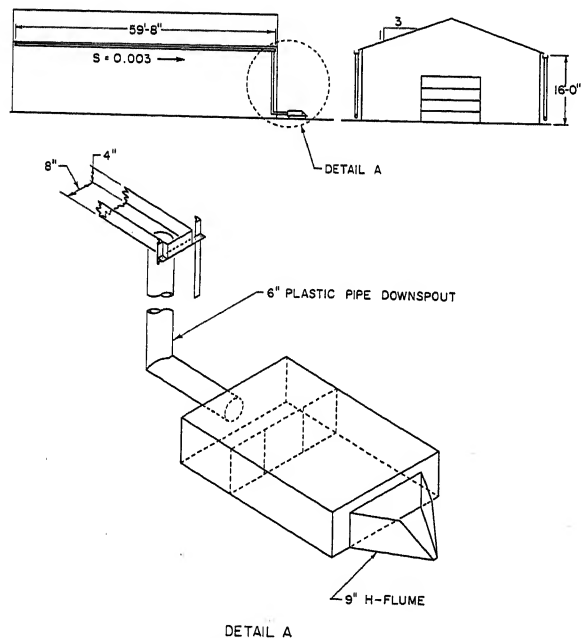

FIGURE 4.—Rainfall rates for 5-minute intervals and runoff rates for windward side of building for storm of April 15, 1972.

FIGURE 5.—Rainfall rates for 5-minute intervals and runoff rates for leeward side of building for storm of April 15, 1972.

mometer was read. This reading provided a check on the recording instrument.

RESULTS

Observations began on April 1, 1972, and continued for one full year, but only the first 8 months of rainfall and runoff data were analyzed.

Storm of April 15, 1972

The first rain fell on April 15 and totaled 0.96 inch. Rainfall intensity and runoff rates for this event are shown in figure 4 for the windward side and in figure 5 for the leeward side. Accumulated rainfall and runoff are shown in figure 6. The windward side delivered a runoff amount equal to 98 percent of the rain measured at the rain gage and the leeward side, 82 percent. The data summary for this storm is shown

FIGURE 3.—Roof-gutter and H-flume installation on model building.

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TABLE 1.—*Data summary for storm of April 15, 1972*[1]

Calculation or measurement	Result
Wind:	
Amount .... mi	22
Velocity .... mi/h	15
Resultant:[2]	
Amount .... mi	20
Azimuth .... deg	350
Angle of wind[3] .... deg	N14
Rain:	
Amount .... in	0.96
Maximum 5-min intensity .. in/h	3.60
Runoff:	
Amount (north) .... in	0.937
Amount (south) .... in	0.791
Peak rate (north) .... in/h	4.36
Peak rate (south) .... in/h	3.74

[1] Storm began at 0216 and ended at 0345.

[2] The resultant is the vector sum of the eight wind directions and amounts.

[3] Angle of wind with respect to normal direction to side of building.

in table 1. Like data were tabulated for each rain event during the year.

Theoretical Analysis

A comparison of the runoff values in the experiment with values predicted from equation 2 showed poor agreement. Therefore, a coefficient was sought for the right-hand term that would improve the predictive ability of the equation. Rewriting the equation to include the coefficient gives

$$\frac{Q_w}{P}=1+K\frac{V_w}{16.8}\cos \alpha \tan S.$$

FIGURE 6.—Accumulated rainfall and runoff for windward and leeward sides of building for storm of April 15, 1972.

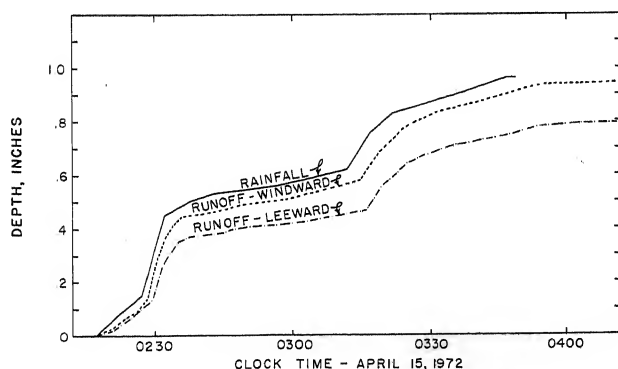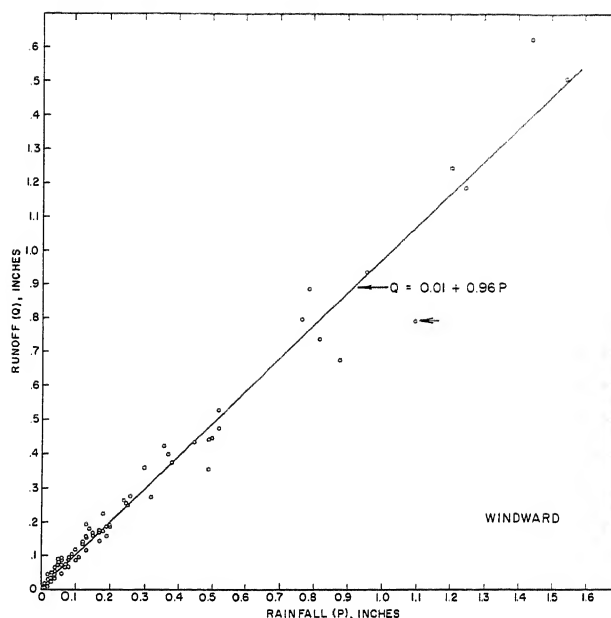FIGURE 7.—Runoff for windward side of building versus rainfall for rainfall events from April 1 to December 31, 1972. (Arrow is for event with highest wind velocity.)

Solving for the coefficient yields

$$K=\frac{\dfrac{Q_w-P}{P}}{\dfrac{V_w}{16.8}\cos \alpha \tan S}.\qquad(3)$$

For a roof sloping toward the wind, $\tan S = \frac{1}{3}$. For a roof sloping away from the wind, $\tan S = -\frac{1}{3}$. Thus, for this building for the windward slope

$$K=\frac{50.4 \ (Q-P)}{P V_w \cos \alpha}\qquad(4)$$

and for the leeward slope

$$K=\frac{-50.4 \ (Q-P)}{P V_w \cos \alpha}.\qquad(5)$$

The value of K was calculated for each storm event, and all values, both windward and leeward, were averaged to obtain the following values:

Mean: $K=0.431$.

Standard error: $\sigma K=0.458$.

Fiducial limits at 5 percent level: $-0.720 < K < 1.562$.

The standard error is large, and the range of the fiducial limits is wide. Therefore, the theoretical approach does not appear valid. However, the theory is based on an oversimplified

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flow path for the raindrops. The actual path of a raindrop is affected by eddies generated by the building in the flow stream and may not remotely resemble the straight-line path used in theory. However, the individual paths may be random, with the average path being a reasonable representation of the entire family of raindrops. Even so, the theoretical model does not take into account the effect of splash and of edge losses. So it is quite possible that the catch of the downwind slope can be altered differently from that of the upwind slope. So K values were calculated separately for the windward and leeward roofs. The results are

Windward: $K_u = 0.327$ or $\sigma K_u = 0.467$.

Leeward: $K_d = 0.358$ or $\sigma K_d = 0.844$.

The separate K's are more erratic than the combined K's.

Correlation Analysis

Since the theoretical approach did not yield a practical method for establishing the relationship between rainfall and runoff, correlation analysis was made.

Rainfall-runoff relationships are shown in figures 7 and 8 for the windward and leeward sides; events with no wind and with snow storms are not included. Least-squares fit of the data yielded, for the windward side,

$$Q = 0.01 + 0.96P \qquad (R = 0.986)$$

and, for the leeward side,

$$Q = 0.89P, \qquad (R = 0.987)$$

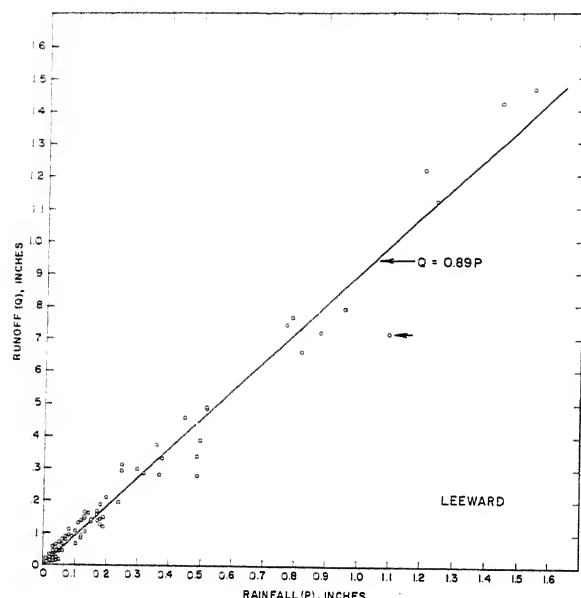where Q = runoff (inches)

and P = rainfall (inches).

FIGURE 8.—Runoff for leeward side of building versus rainfall for rainfall events from April 1 to December 31, 1972. (Arrow is for event with highest wind velocity.)
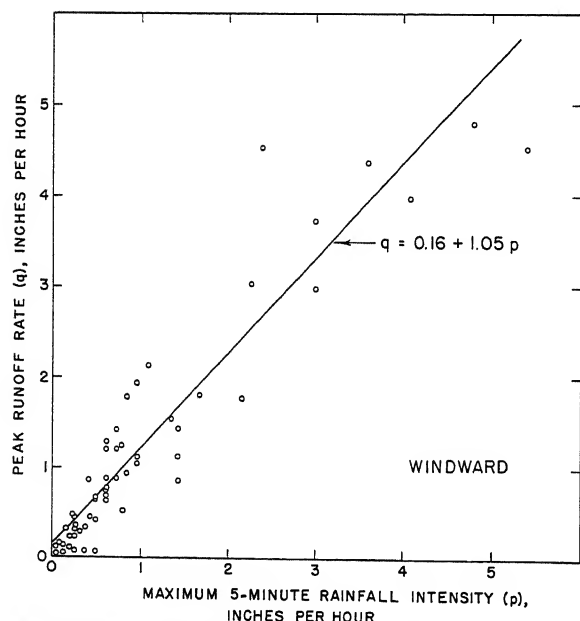

FIGURE 9.—Relationship of peak runoff rate to maximum 5-minute rainfall intensity during storm for windward side of building.
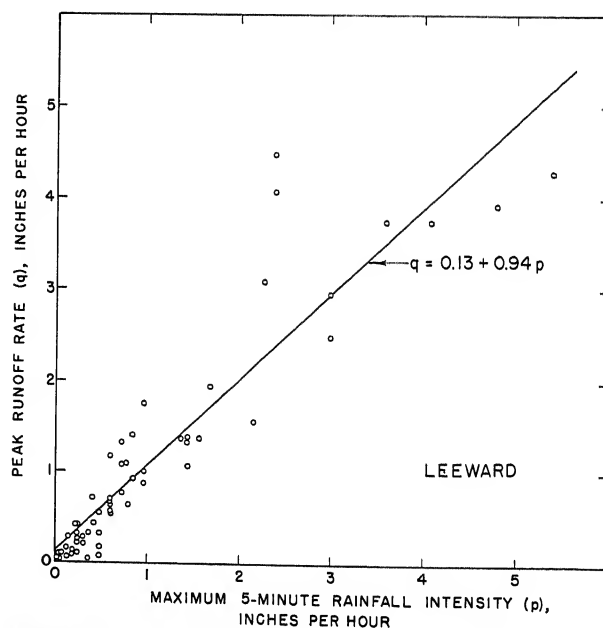

FIGURE 10.—Relationship of peak runoff rate to maximum 5-minute rainfall intensity during storm for leeward side of building.

The scatter of these points is probably due to turbulent eddies as well as to differing wind velocities and directions. The theoretical analysis did not satisfactorily establish the effect of wind on the runoff, but it is noteworthy that the point that departed farthest from the trend line was for the event with the highest wind velocity, 21 miles per hour (points marked with arrows).

The relationships of the peak runoff rate to the maximum 5-minute rainfall intensity are shown in figures 9 and 10 for the windward and leeward sides. Considerable scatter is shown. Simple linear relationships for these data are as follows:

Windward: $q=0.16+1.05p$ $(R=0.939)$
Leeward: $q=0.13+0.94p$ $(R=0.922)$
where $q=$runoff rate (inches per hour)
and $p=$rainfall rate (inches per hour).

Again, no attempt was made to introduce wind velocity or angle of approach into the relationship because of lack of consistency in the data. Velocity probably has some effect because the point that departed farthest from the trend line was for a storm with a wind velocity of 16 miles per hour.

Snowmelt Runoff

During November seven snowstorms occurred, which had a total of 0.99 inch of precipitation as determined by melting the rain-gage catch. Winds for the snowfall events ranged from 2 to 9 miles per hour. Some of the snow

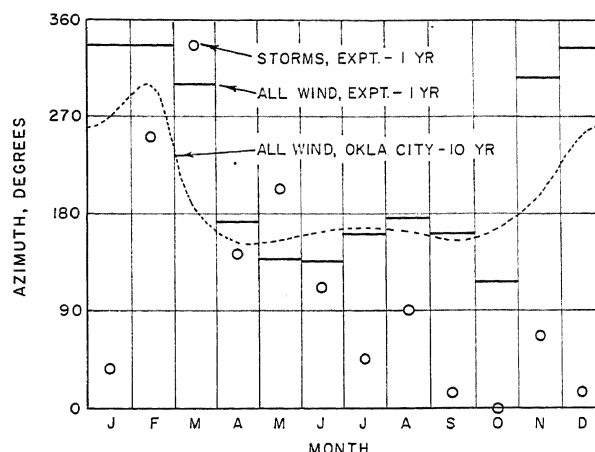FIGURE 11.—Overhanging sheets of ice on north roof about to break off and miss collecting gutter.

FIGURE 12.—Wind direction resultants for each month from April 1, 1972, through March 31, 1973, compared with 10-year average for Oklahoma City.

that fell on the roof was probably blown off, but the amount could not be determined. The snowmelt runoff was 0.48 inch from the north side and 0.54 inch from the south side. Thus, only about 50 percent of the snow was captured as runoff. The other half either blew away, sublimated, or slid off the roof as sheets of snow or ice. Figure 11 shows overhanging sheets of ice about to break off and miss the collecting gutter.

Wind Experience

Results of wind observations are given in table 2. For the 1-year experiment, over 59,000 miles of wind flowed past the observation point, resulting in a mean velocity of 6.8 miles per hour. During the storm periods, which totaled 392 hours, the flow was 2,827 miles, a mean velocity of 7.2 miles per hour. Precipitation occurred 4.8 percent of the time during the year.

TABLE 2.—*Wind data summary for 1 year, from April 1, 1972, to March 31, 1973*

Calculation or measurement	Results	
	1 year	Storm periods
Amount .... mi	59,321	2,827
Duration .... h	8,760	392
Mean velocity ... mi/h	6.8	7.2
Resultant:[1]		
Amount ...... mi	6,640	732
Azimuth ..... deg	162	48

[1] The resultant is the vector sum of the eight wind directions and amounts.

Wind experience for the 1-year experiment is compared with the 10-year average for Oklahoma City (the nearest reporting station) in figure 12. Azimuths of the resultant wind for each month of the year are shown. During the summer months the wind directions at the laboratory were like the 10-year averages at Oklahoma City, but for the winter months they were more northerly. Storm wind directions scattered and did not often coincide with average wind directions for the month; however, they were not randomly distributed. Table 3 shows

APRIL 1972

TOTAL-6454 mi 720 h
STORM-180 mi 19 h

MAY 1972

TOTAL-4346 mi 744 h
STORM-111 mi 12 h

JUNE 1972

TOTAL-4255 mi 720 h
STORM-81 mi 11 h

JULY 1972

TOTAL-4762 mi 744 h
STORM-145 mi 22 h

AUGUST 1972

TOTAL-4293 mi 744 h
STORM-75 mi 16 h

SEPTEMBER 1972

TOTAL-4444 mi 720 h
STORM-107 mi 15 h

OCTOBER 1972

TOTAL-4480 mi 744 h
STORM-241 mi 45 h

NOVEMBER 1972

TOTAL-4910 mi 720 h
STORM-233 mi 40 h

DECEMBER 1972

TOTAL-5094 mi 744 h
STORM-165 mi 33 h

JANUARY 1973

TOTAL-4956 mi 744 h
STORM-588 mi 82 h

FEBRUARY 1973

TOTAL-4779 mi 672 h
STORM-141 mi 18 h

MARCH 1973

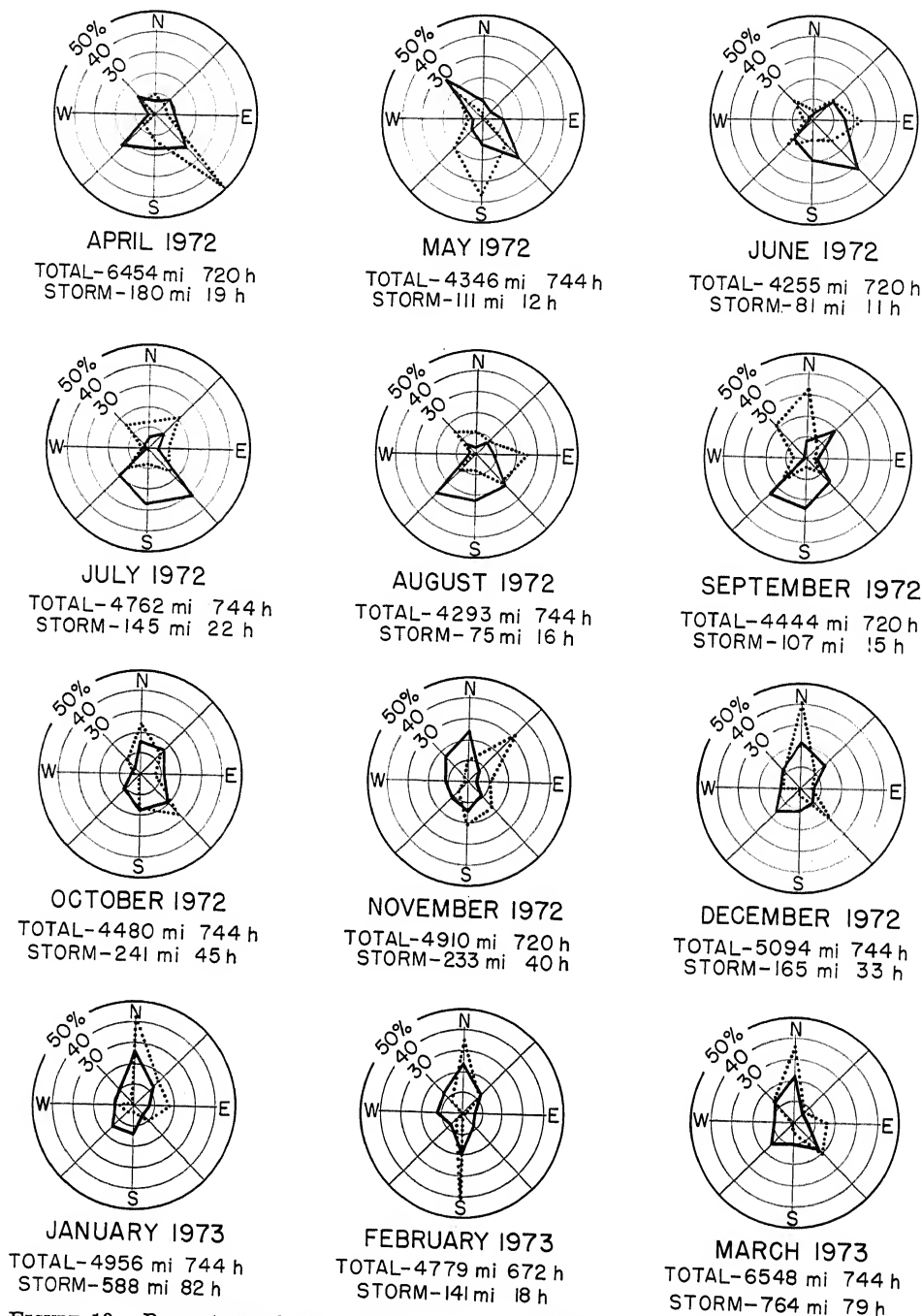TOTAL-6548 mi 744 h
STORM-764 mi 79 h

FIGURE 13.—Percentage of miles of wind from each of eight directions for storm periods compared with monthly wind distribution from April 1, 1972, to March 31, 1973. (Solid line shows wind distribution for total time; dotted line shows wind distribution for storm time.)

that the predominant direction was southeast.

Another attempt to portray the wind experience is shown in figure 13. For each month the percentage of miles of wind from each of eight directions is compared with the storm experience, but no relationship is evident.

DISCUSSION

Direction of wind, whether blowing toward the sloping roof or away from it, made a difference in the amount of runoff. The windward side delivered 96 percent of the rainfall as runoff and the leeward side 89 percent, an average of 92.5 percent for the entire roof.

Only 50 percent of the snowfall was delivered as runoff, with the south roof contributing a little more than the north roof. Since snowfall is but a small part of total precipitation in this locality, the loss of half of the snow as runoff does not have much impact on net water yield. A recovery of 90 percent of all precipitation as runoff would be a satisfactory assumption for design purposes for this area.

Rates of runoff were also studied because they enter into the capacity design of the collecting and conveying components of a rain-harvesting system. Capacity must be provided to accommodate rainfall intensity for a selected frequency of occurrence and for a duration equal to the time of concentration. This time for the model building is about 2 minutes. However, the shortest duration given in available weather data is 5 minutes. Since the available data serve as the basis for design, the

TABLE 3.—*Distribution of storm-wind direction for 1 year, from April 1, 1972, to March 31, 1973*

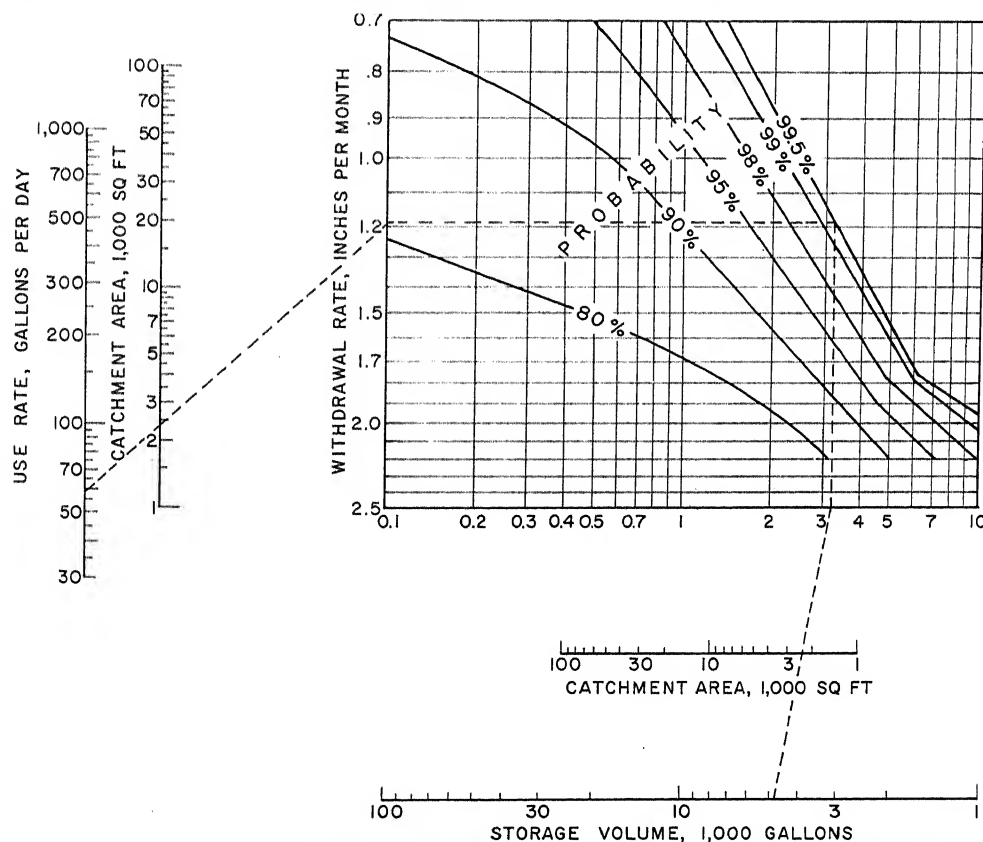| Direction	No. storms
North	19
Northeast	25
East	21
Southeast	30
South	18
Southwest	11
West	10
Northwest	10

FIGURE 14.—Catchment areas and storage-tank volumes for rain-harvesting systems in Stillwater, Okla., area. (Parameters are use rate and probability.)

peak runoff rates for this experiment were related to the maximum 5-minute rainfall intensity for the storm. On the average, the peak runoff rate was about equal to the maximum 5-minute rainfall intensity. However, some large departures from this average were observed with runoff rates nearly twice the 5-minute rainfall intensity. Since runoff rate cannot exceed rainfall rate, the instantaneous rainfall rates evidently exceeded the average rate for the 5-minute period. However, intensities for shorter periods could not be determined accurately with the available rain gage. For this installation, the 5-minute period is probably satisfactory for the selection of design rainfall intensity. The peak rainfall rate for a 5-minute period during the year of study was 5.40 inches per hour. The corresponding runoff rates for the windward and the leeward sides were 4.52 and 4.28 inches per hour, respectively. These runoff rates were well below the design capacity of 9 inches per hour for the roof gutter, so at no time was the collecting system taxed. However, none of the other tests of the performance of this system was conducted under peak design conditions.

Wind during a rainstorm can come from any direction (see table 3), so it does not seem practical to attempt to orient a building to maximize runoff production. Building location, use, and access should govern the way the building is placed.

Methods for the hydrologic design of rain-harvesting systems can be modified for application to rooftops. A system devised by Ree et al.[5] is used as an example. The diagram in figure 14 is taken from figure 9 in the report by Ree. For determining the estimated safe daily yield of the model-building roof, use this diagram with the roof area (2,400 ft²), a probability factor (99.5 pct), and a storage tank with a 4,800 gallon capacity. Reading an uncorrected use rate of 58 gallons per day and multiplying by the ratio 0.9 (as determined in this experiment) results in a safe-use rate of 52 gallons per day.

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[5] Ree, W. O., Wimberley, F. L., Gwinn, W. R., and Lauritzen, C. W. 1971. Rainfall harvesting system design. U. S. Dep. Agric., Agric. Res. Serv. [Rep.] ARS 41–184, 12 pp.

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